Tunnelling and Underground Space Technology 79 (2018) 76–82

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

# Driving force for preventing smoke backlayering in downhill tunnel fires using forced longitudinal ventilation

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## ARTICLE INFO

*Keywords:*
Smoke control
Stack effect
Downhill tunnel
Driving force
Longitudinal ventilation

## ABSTRACT

The critical ventilation velocity plays an important role in smoke control in longitudinally ventilated tunnel fires. The magnitude of the critical velocity has been widely studied. In the present study, we carried out theoretical analyses and numerical simulations to investigate the driving force necessary for achieving the critical velocity in downhill tunnels. Theoretical models suggest that buoyant source location has a considerable effect on the condition for achieving the critical velocity. For a constant convective heat release rate of the fire, the driving force necessary for achieving the critical velocity increases with the height difference between the fire source and the outlet of the smoke. According to FDS simulation results, with the increase of the height difference between the fire source and the smoke outlet, the pressure loss induced by the stack effect increases significantly; however, the variation in the ventilation critical velocity is insignificant. Therefore, the variation in the driving force is mainly because of the stack effect rather than the variation in the critical velocity. In addition, the effects of the fire occurrence on the longitudinal ventilation velocity and pressure distribution in the tunnel are also numerically studied. If the pressure rise of the jet-fan keeps constant, the longitudinal velocity declines remarkably after the fire occurrence as a result of the pressure loss induced by the fire and the pressure loss induced by the stack effect. The phenomenon presented in the paper has implications for both tunnel ventilation and smoke control in inclined tunnels.

## 1. Introduction

Fire accidents in road tunnels can greatly endanger the safety of passengers and firefighters. Because a tunnel is a confined space with a large length-to-width ratio, evacuation during a fire accident is very difficult. Compared to the fire flames, hot toxic smoke generally causes more casualties (Gao et al., 2016; Tang et al., 2017a). Therefore, various smoke control strategies have been adopted in tunnels (Fan et al., 2014; Harish and Venkatasubbaiah, 2014; Tang et al., 2017b; Vauquelin, 2008), among which longitudinal ventilation is a currently practiced method because of its simplicity and efficiency (Du et al., 2015, 2016). The critical velocity is defined as the minimum longitudinal velocity required to prevent smoke from propagating upstream of the fire. Previous studies have confirmed that for small and medium fires, the critical velocity varies as the cubic root of the convective heat release rate; however, for large fires, the velocity becomes independent of the convective heat release rate (Kunsch, 2002; Li et al., 2010; Oka and Atkinson, 1995; Thomas, 1968; Tsai et al., 2011; Wu and Bakar, 2000). The slope of a tunnel can affect the critical velocity. Wu et al. (1997) performed experiments in a small-scale tunnel and obtained the following expression:

$$V_c(\theta) = V_c(0) \times (1 + 0.014\theta) \tag{1}$$

Similar formulas have also been obtained by other researchers, although the coefficients in their equations are slightly different (Chow et al., 2015; Ko et al., 2010; Weng et al., 2016; Yi et al., 2014). Considering that $\theta$ is small for common traffic tunnels, the discrepancy between $V_c(\theta)$ and $V_c(0)$ could be negligible. Therefore, the tunnel inclination has a relatively small effect on the magnitude of the critical velocity. However, the pressure difference generated by the stack effect might be substantial, especially in a long, inclined tunnel where the height difference between the tunnel portals is large. Furthermore, the pressure rise of jet fans required for longitudinal smoke control can also be influenced by the stack effect.

Different aspects of the critical velocity in a tunnel have been investigated extensively. However, little effort has been made to study the condition necessary for achieving the critical velocity in a longitudinally ventilated downhill tunnel. In a full-scale fire test, Ingason et al. (2012) found that the longitudinal velocity reduced from 2.5 to 2.0 m/s as the fire became more intensive, indicating that the fire was

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https://doi.org/10.1016/j.tust.2018.05.005
Received 14 October 2017; Received in revised form 7 May 2018; Accepted 8 May 2018
0886-7798/

**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area of tunnel ($m^2$) |
| $C_p$ | heat capacity at constant pressure ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)) |
| $D$ | hydraulic diameter of tunnel (m) |
| $E$ | convective heat release rate of fire (W) |
| $\Delta H$ | height difference between fire source and smoke outlet (m) |
| $h$ | height of tunnel (m) |
| $k$ | longitudinal decay rate of smoke temperature ($m^{-1}$) |
| $k'$ | thermal conductivity of smoke ($W{\cdot}m^{-1}{\cdot}K^{-1}$) |
| $L$ | total length of tunnel (m) |
| $L_0$ | length of tunnel upstream of fire source (m) |
| $L_s$ | length of tunnel downstream of fire source (m) |
| $m$ | mass flow rate of smoke (kg/s) |
| $Nu$ | Nusselt number |
| $P$ | perimeter of tunnel cross-section (m) |
| $R_0$ | gas constant for ambient air ($J{\cdot}mol^{-1}{\cdot}K^{-1}$) |
| $R_s$ | gas constant for smoke ($J{\cdot}mol^{-1}{\cdot}K^{-1}$) |
| $Re$ | Reynolds number |
| $V$ | flow velocity (m/s) |
| $V_c$ | critical velocity (m/s) |
| $V_c(\theta)$ | critical velocity of tunnel with slope $\theta$ (m/s) |
| $V_c(0)$ | critical velocity of horizontal tunnel (m/s) |
| $V_s$ | longitudinal velocity of smoke (m/s) |
| $V_0$ | longitudinal velocity of air (m/s) |
| $x$ | longitudinal distance between fire source and concerned point (m) |
| $\Delta P_a$ | pressure loss across control volume due to velocity acceleration effect (Pa) |
| $\Delta P_{fire}$ | pressure loss induced by the fire |
| $\Delta P_{stack}$ | pressure loss induced by stack effect |
| $\Delta P_t$ | pressure loss due to thermal expansion (Pa) |
| $\Delta P_j$ | mechanical driving force necessary for thermal smoke prevention (Pa) |
| $T_0$ | air temperature (K) |
| $T_s$ | smoke temperature (K) |
| $\Delta T$ | temperature difference between smoke and air in adiabatic tunnels (K) |
| $\Delta T^*$ | temperature difference between smoke and air in non-adiabatic tunnels (K) |
| $\lambda$ | frictional coefficient |
| $\xi_{fire}$ | flow resistance coefficient induced by the fire |
| $\xi_{in}$ | local flow resistance coefficient at tunnel inlet |
| $\xi_{out}$ | local flow resistance coefficient at tunnel outlet |
| $\rho_s$ | smoke density ($kg/m^3$) |
| $\rho_0$ | ambient air density ($kg/m^3$) |
| $\Delta\rho$ | density variation ($kg/m^3$) |
| $\alpha$ | convective heat transfer coefficient ($W/m^2{\cdot}K$) |
| $\theta$ | tunnel slope in degrees |
| $\nu$ | kinematic viscosity ($m^2/s$) |

an important source of flow resistance for ventilation. An analytical model was proposed to explain the phenomenon of velocity reduction (Ingason et al., 2012). Kazemipour et al. (2017) numerically studied the impact of fire on ventilation system performance. The results indicated that the longitudinal velocity dropped by 50% as the fire intensified. The velocity reduction was attributed to flow resistance caused by fire, and a theoretical model was developed to predict the fire-induced pressure loss (Kazemipour et al., 2017). In an inclined tunnel, the stack effect could have a more pronounced effect on the ventilation flow than the fire source. It has been demonstrated that stack effect is an important factor influencing the smoke movement in inclined tunnel fires (Merci, 2008; Chow et al., 2015, 2016; Fan et al., 2017). If the mechanical ventilation devices are not activated, fire smoke is more likely to flow towards the upper portal of the inclined tunnel as a result of the stack effect (Chow et al., 2015; Du et al., 2018). For an uphill tunnel, vehicles move in the same direction with the fire smoke, and thus the upward smoke movement is helpful for longitudinal smoke control. For a downhill tunnel, the vehicles and fire smoke move towards opposite directions, which is detrimental to the vehicles and passengers at the upstream region of the fire source. The pressure difference generated by the stack effect is a driving force for achieving the critical velocity in an uphill tunnel (Yang et al., 2018). However, it becomes a constituent of flow resistance in a longitudinally-ventilated downhill tunnel. Therefore, the condition for achieving the critical velocity in an uphill tunnel will not be discussed in this paper.

In the present study, the flow resistance generated in a downhill tunnel fire is analyzed. The influence of the stack effect on the driving force necessary for achieving the critical velocity in downhill tunnels is investigated. The paper is organized as follows. First, the pressure drops caused by the fire source, stack effect, and wall friction are theoretically analyzed. Then, Fire Dynamics Simulator (FDS) simulations are implemented to investigate the role of the stack effect and the variation in the flow velocity in downhill tunnel fires. Lastly, conclusions are drawn.

## 2. Analysis of the driving force required for preventing smoke backlayering in a downhill tunnel

In a longitudinally ventilated downhill tunnel, the driving force necessary for achieving the critical velocity is equal to the total pressure loss $\Delta P$, which includes the pressure loss induced by the fire $\Delta P_{fire}$, the pressure loss due to wall friction $\Delta P_{\lambda}$, the pressure loss at the tunnel portals $\Delta P_{\xi}$, and in particular, the pressure loss induced by the stack effect $\Delta P_{stack}$.

### 2.1. Pressure loss induced by the fire

The press loss induced by the fire consists of two parts: the pressure loss induced by thermal expansion and the one induced by fire plume blockage. The longitudinal flow is accelerated in the fire zone because of thermal expansion. Fig. 1 shows a control volume including the fire source. Because the pressure loss induced by thermal expansion is independent of the viscosity, we suppose that the flow is inviscid and parameters such as velocity, temperature, and pressure are uniformly distributed on the side boundaries of the control volume. Eq. (2) is established according to the momentum conservation equation for inviscid flow.

$$\Delta P_a = \rho_s V_s^2 - \rho_0 V_0^2 \tag{2}$$

Therefore, the pressure loss due to thermal expansion $\Delta P_t$ can be estimated according to the following equation (Cheng et al., 2007):

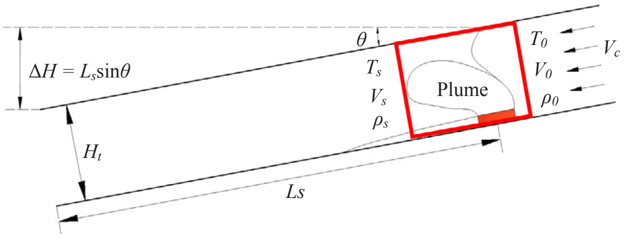

**Fig. 1.** Control volume in fire region.